

Quantum Field Theory for Philosophers

The Quantum Theory of Fields in the Contemporary
Focus is Metaphysical Research
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Introduction

QFT has emerged during last 10 years as the most
framework in which to do elementary particle
physics

Are philosophers prepared to use current physical
theory as a guide to resolving metaphysical
questions?

Object paper is to tell straightforwardly what
QFT has to say about 'reality'.

I am not going to deal with the interpretative
problems of QM as such

The Classical Concept of Field

Different approaches to theory of matter

Nature of forces between 'pieces' of matter.

→ action-at-a-distance v. field theories

Field Theory

Associates certain properties with points

of space-time points

e.g.

E.M. field, Extension hydrodynamics

Particle Theory

Attributes to certain individuals (or particles)

a variety of properties.

These properties will include space-time locations

What do we mean by an individual?

In classical physics a simpler notion is normally used.

Individuation transcends the properties of an entity — Unknowable substratum — Instrumental Individuality (TI).

But in classical particle physics spatio-temporal continuity of trajectory can be used (cf. Boltzmann (1847))

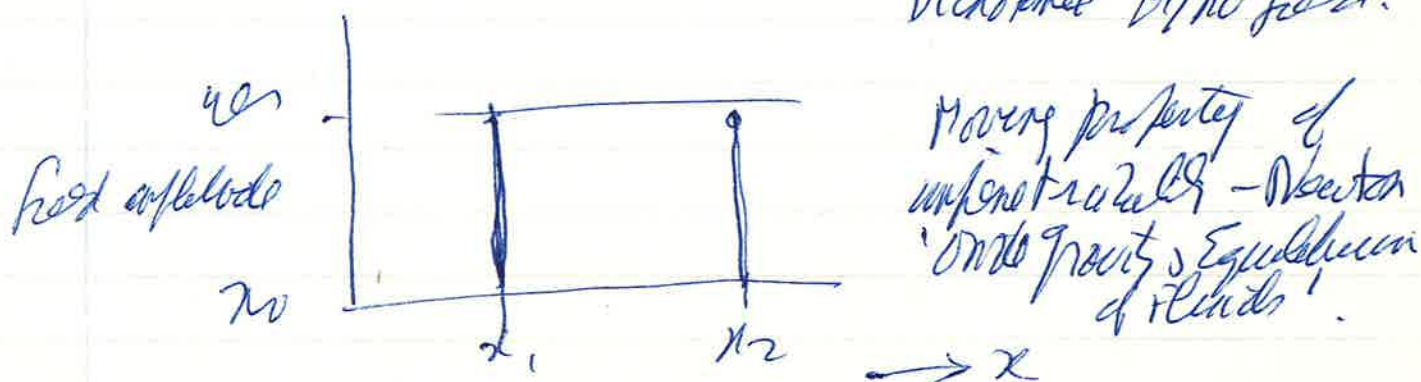
This is not available in QM and if elementary particles are to be regarded as individuals TI must be assessed. This will be used as an argument against particle approaches to the interpretation of QFT.

Query: Do spatio-temp points possess TI?

Basic difficulty for field theories of matter
How do objects get individuated?

Field Approach to classical particle physics

Dichotomy of/no field.



Undetermination as between particles and field
approaches — Arrangement (no matter of fact at stake)
(Newton-Smith) v. Isolation (matters of fact not at stake
or correlation)

History of classical field theories

1. Field theories of matter in 19th C. (Butter, Priestly)
cf Faraday "A Speculation touching -- the Nature
of Matter", 1844.
2. Reduction of force to particles, effluvia theories
3. 'Wave theories' of force - propagation of state
of stress in a medium
→ 19th C. Ether theories
4. Reduction of matter to ether (Thomson
vortex atom) - Larmor
5. Lorentzian dualism: charged particles
and electromagnetic, but not mechanical ether.
 - ↳ Even or new ontological category
 - ↳ electromagnetic theories of matter
Abraham, Wien → NO, Born, Infeld.
6. Einstein - abstracted notions of gravity
via $E = mc^2$ of Equivalence Principle
 - C.F. → metric tensor field
 - ↳ Unified theories of gravitation & p.m.
matter = local concentration of
gravitational field
 - ↓ geometrodynamics of Wheeler.

Quantum Field Theory

Two main approaches

First Quantization

1. Classical field is regarded as a 'mechanical' system with an ∞ no. degrees of freedom
— subjected to canonical quantization
field amplitudes \rightarrow operators.

Ex Real Klein-Gordon field

$$(\nabla^2 - \nabla^2 \frac{\partial^2}{\partial t^2} + \mu^2) \phi = 0$$

Define ϕ is 'configuration' field
conjugate 'momentum' field $\pi = \frac{\partial \phi}{\partial t}$

Total energy of field $H = \int H d^3x$

where $H = \frac{1}{2} \{ \pi^2 + c^2 |\nabla \phi|^2 + c^2 \mu^2 \phi^2 \}$

Fourier analyze the 'configuration' or 'momentum' fields

$$H = \frac{1}{2} \sum_{\underline{k}} (p_{\underline{k}}^+ p_{\underline{k}} + \omega_{\underline{k}}^2 q_{\underline{k}}^+ q_{\underline{k}})$$

$$\omega_{\underline{k}} = c \sqrt{\mu^2 + k^2}$$

Define $q_{\underline{k}} = \frac{1}{\sqrt{2\pi\omega_{\underline{k}}}} (\omega_{\underline{k}} q_{\underline{k}} + i p_{\underline{k}}^+)$

$$q_{\underline{k}}^+ = \frac{1}{\sqrt{2\pi\omega_{\underline{k}}}} (\omega_{\underline{k}} q_{\underline{k}}^+ - i p_{\underline{k}})$$

$$\left. \begin{aligned} \text{then } [q_{\underline{k}}, q_{\underline{k}'}^+] &= \delta_{\underline{k}, \underline{k}'} \\ [q_{\underline{k}}, q_{\underline{k}'}] &= [q_{\underline{k}}^+, q_{\underline{k}'}^+] = 0 \end{aligned} \right\}$$

$N_{\underline{k}} = q_{\underline{k}}^+ q_{\underline{k}}$ has eigenvalues 0, 1, 2, ...

$$\left. \begin{aligned} H &= \hbar \sum_{\underline{R}} (N_{\underline{R}} + \frac{1}{2}) \omega_{\underline{R}} \\ \underline{P} &= \hbar \sum_{\underline{R}} N_{\underline{R}} \underline{R} \end{aligned} \right\}$$

Eigenvalues of H & \underline{P} are

$$E = \sum_{\underline{R}} N_{\underline{R}} (\hbar \omega_{\underline{R}}) + \text{const.}$$

$$\underline{P} = \sum_{\underline{R}} N_{\underline{R}} \hbar \underline{R}$$

also $\text{const.} = \frac{1}{2} \sum_{\underline{R}} (\hbar \omega_{\underline{R}})$

So the number of quanta present with momentum $(\hbar \underline{R})$ and energy $(\hbar \omega_{\underline{R}})$ in the particle representation is just the excitation number $N_{\underline{R}}$ of the \underline{R} -mode.

Second-Quantization

2. Start with N -particle Schrödinger Eq. for assembly of bosons - state retains identity symmetric under permutation of particle labels. - specified by giving no. N_i of particles in i-th 1-particle state $|U_i\rangle$ (associated with energy E_i)

then $E = \sum N_i E_i$

cf energy assembly of harmonic oscillators

* $\therefore \bar{E} = \sum_i (N_i + \frac{1}{2}) E_i$ if $U_i = E_i/\hbar$

But Ψ is what we would get by solving the 1-particle S. Eq. to a second-quantization

i.e. interpreting it as a field classical field equation and solving it to Field quantization

But second-quantization is more general than the N -particle Schrödinger equation

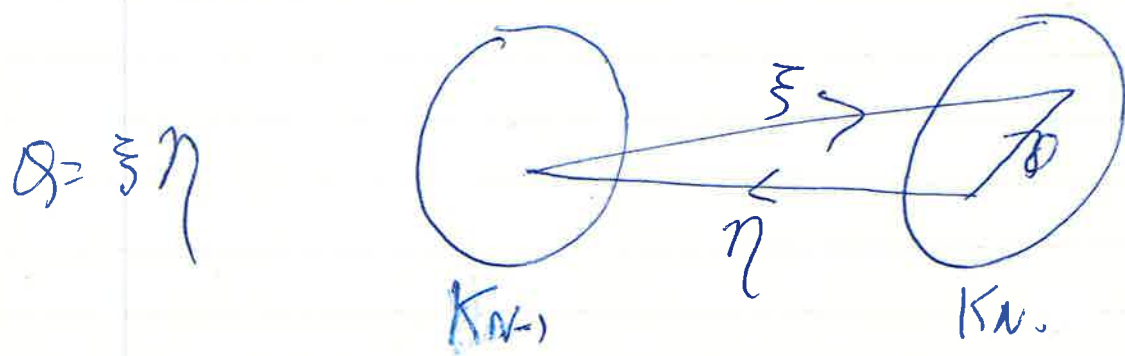
because of constraint $\sum_i n_i = N$.

Fock space $\mathcal{F} = K_0 \oplus K_1 \oplus \dots \oplus K_N \oplus \dots$
 \downarrow
 vacuum.

Creation and Annihilation Operators

$$a_i |n_i\rangle = \sqrt{n_i} |n_i - 1\rangle$$

$$a_i^+ |n_i\rangle = \sqrt{n_i + 1} |n_i + 1\rangle$$



But $Q' = \xi + \eta$ would create and annihilate particles

N.B. Consider state \rightarrow vacuum -
 $a_1^+ a_2^+ \dots a_n^+ |\Phi_0\rangle$

this is symmetric order permutation of state labels due to the commutation of the a_i 's.
 This is what corresponds in 2nd quantized formulation to symmetric order permutation of particle labels in the N -particle formulation.

So 'Real' field $\xrightarrow{\text{Field Quantization}}$ Quantum Field

N -particle P.S. $\xrightarrow{\text{Second Quantization}}$

Query But in Quantum Field the same is true in the 2nd cases?

In particular for fermions 2nd quantization uses anticommutator brackets $\{a_i, a_j^+\} = \delta_{ij}$

Response 1.) $\left. \begin{array}{l} \text{K. C. field real} \\ \text{S. field complex} \end{array} \right\}$

But complex field = pair of real fields
 describes charged particles in QFT
 \rightarrow notion of antiparticle
 (trying to do with -20 energy states)

2.) Canonical limit of boson field is canonical
 Canonical limit of Fermion field is ^{field} collection
 of particles.

But historical accident that QFT arrived at
 by Canonical quantization imposed on
 a Canonical limit - does not mean
 different interpretation when we do not pass
 to the limit.

3.) $\left. \begin{array}{l} \text{Matter fields are 'field', theories} \\ \text{Matter fields are particles} \end{array} \right\}$

Distinction based on claimed nonlocalizability
 of massless quanta.
 1st quantization: no position operator
 - Neutrinos, Wigner (not of Pauli-Dirac)
 2nd quantization: particle production
 if localized with Compton wavelength
 $\lambda/mc \rightarrow 0$ as $m \rightarrow 0$

But does easy production of soft photons
 conflict against the localization of a
 hard photon ray?

4.) Weinberg (1964) approach to field theories
 via: Creation/annihilation operators for
 Canonical states + change of basis
 to get transformation properties under
 finite-dimensional nonunitary representations
 of the Poincaré group. In general the
 fields constructed by Weinberg do not satisfy
 relativistic wave equations (Klein-Gordon or Dirac)
 K. E. equations

5.) Argument for field having causal significance is based on causality condition

$$[\phi(x), \phi'(y)] = 0 \text{ if } (x-y)^2 < 0$$

(NB local observables average over small space-time regions)
Violation would change statistics at x by performing measurement at y .
(Contrast with EPR nonlocality)

cf ϕ 's always contain an even number of fermion field factors etc

Sufficient condition for locality is for fields to commute or anticommute at space-like intervals

Spin-Statistics Theorem

Boson fields — spin of particles is integer
Fermion fields — spin of particles half-integer

This theorem rules out anticommutation for ^{integer spin} bosons
or commutation for half-integer spin.
only leads to fermion commutation relations if commutation/anticommutation are only possible.

Confore use of Green (1953) or Parafields

$$[a_R, \{a_L^\dagger, a_M\}] = 2\delta_{R+M}$$

Trilinear commutation rules for parafermi fields
fundamental regardless to parafermion fields

Green Criterion for field quantization

Must express equations of motion for field in terms of Hamiltonian H

$$i\hbar \frac{\partial \psi}{\partial t} = i\hbar [H, \psi]$$

Generalized Spin-Statistics Theorem
(Del Medico, Prentiss & Sudarshan 1963)

Indicates Pauli exclusion for half-integer spins
or parafermions for integer spins

So the Cauchy does not demand the QFT as strongly as in previous support

N.B. Speiser (1964) suggested quasiparafermions (order 3)

Creation and Annihilation Operators in Classical Mechanics

Commutator relations of creation/annihilation operators do not involve \hbar .
Description also possible in classical mechanics.

Consider 'spike' fields as limit of continuous distribution $\rho(p_i, q_i, t)$
Eq. of motion for ρ

is $\rho(t) = e^{-iL(t-t_0)} \rho(t_0)$

where L is Liouville operator

$$L = \sum_i \left(-i \frac{\partial H}{\partial p_i} \frac{\partial}{\partial q_i} + i \frac{\partial H}{\partial q_i} \frac{\partial}{\partial p_i} \right)$$

Consider motion of a single particle in phase space //

Now factorizing $e^{-iL(t-t_0)} = \xi \cdot \eta$

vector annihilation
 operator

η annihilates initial state \rightarrow vacuum
 ξ recreates final state from the vacuum.

Manifestly deniable infinity of instant
 t_1, t_2, \dots between t_0 & t .

Particle is destroyed at each instant
or recreated at successive instant.

cf. doctrine of the Kalam spread
by its Mutakallimun.

decisions do not persist across
time atoms, but continually destroyed
or recreated.

God refrains from the decision
not to recreate.

N.B. Particle Creation, really only accepted
with Fermi's (1933) theory of β -decay;
(cf. his theory of positron and neutrino and
theory of positrons (Dirac 1927)).

Wave-Particle Duality

By quantum exact any phenomenon
can be described either by a (quantized)
particle theory or a (quantized) wave theory
- Cf. Complementarity of wave & particle aspects.

Quote from Dirac (1927), refers to

^ a complete harmony between the wave and light-quantum descriptions of the interaction [between atoms and electro-magnetic waves].

But Complementarity connected with $Q\bar{N}$ and non-commutativity of operators.

Wave picture sharp p (Δx ?)
Particle - sharp x (Δp ?)

As in all discussions of complementarity there is good deal of uncertainty in what we are talking about!

2.0 FT Particle representation as $N_{\bar{A}}$ desired.

But $N_{\bar{A}}$ does not commute with $\psi(\bar{A}, t)$ ($\psi(\bar{A}, t)$ desired for all \bar{A} (at a given time) is wave representation)

But for complex field ψ is not state observable, but wave representation for given \bar{A} by \bar{A} desired for local observables \bar{A} (not as given density)

Query For interesting fields to both
fields have to be quantized?

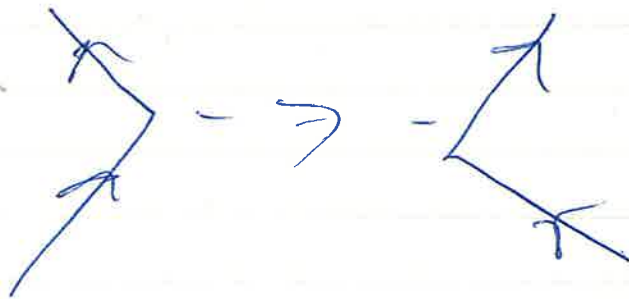
cp - Brown and Redhead (1981).

Matter Fields and Force Fields - Unification

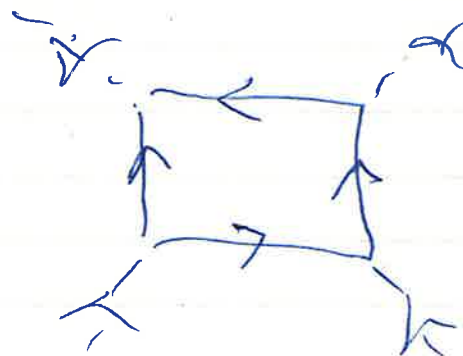
So far we have talked about non-interacting fields
 QFT describes interaction between matter
 quanta (particles) in terms of exchange
 of 'force' quanta, e.g. electromagnetic interaction
 described in terms of exchange of photons
 (actually virtual photons - see below).

But interactions of photons can also
 be regarded as mediated by virtual particles.

cf.



with



So, which is the matter particle and
 which is the force particle?

cf. Bootstrap approach to particle
 democracy in S. Nambu proposed
 every particle plays 3 roles, Constituent,
 Composite and force particle!

Gauge Theories have restored distinction
 between matter & Force
 Force fields
 Gauge fields
 But what
 is status
 of Higgs
 field? Is it
 a force field?
 or a vacuum?

Example, Gauge theories, ~~exhibit~~ ψ satisfies Dirac Eq.
 Lagrangian locally invariant under global
 phase transformations
 But if we impose invariance under $\psi \rightarrow \psi e^{i\alpha}$ local phase
 transformations

$\psi \rightarrow \psi e^{i\alpha(x)}$
 This requires introducing a new
 gauge field. Minimal coupling is Maxwellian
 photon field.
 So gauge invariance 'explains' the photon.

This distinction between fermion and vector
 fields has been blurred in supergravity
 theories

\Rightarrow Unified theory of all the interactions
 is Extended Supergravity - Also called Unification
of Matter and Force

What do we mean by Unification?

One kind of entity enters into the unifying
 theory where previous phenomena were explained
 in terms of distinct independent entities.

ex (1) Optical & electromagnetic waves identified

(2) \vec{E} and \vec{H} combined into 6-component field
 tensor - Under parav. Lorentz transformation
 \vec{E} & \vec{H} have no separate equivalent expressions

(3) Gauge theory unification: Different kinds of
 particles identified as different
 states of the same entity
 ex. neutrons & protons as two states of
 the nucleon.

But this is freedom to particles, since gauge
 transformations have only an 'action' interpretation
 one particle changed into another rather

than merely reduplicated

Query Are group symmetries related to ontological economy?

(But note that 'naturalness' is itself philosophically controversial)

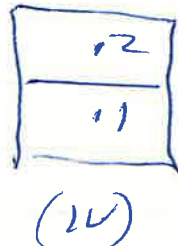
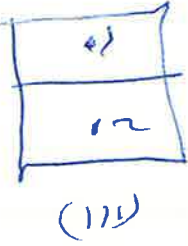
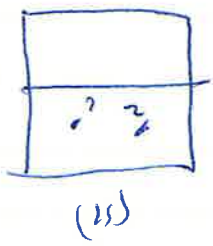
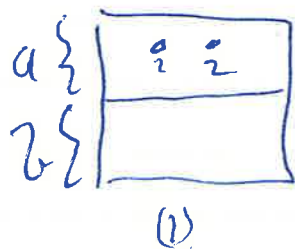
The Problem of Individuality

Claim is often made that elementary particles do not possess TI \rightarrow not individuals

Argument based on Statistical mechanics of bosons & fermions

Consider possible states available to 2 indistinguishable particles distributed among 2 distinct 1-particle states

Classical statistical mechanics (assuming TI) give the following possible distinct arrangements.



But in quantum statistical mechanics (iii) and (iv) are regarded as one of the same state in quantum statistical mechanics. This is taken as showing particles do not possess TI. The argument is fallacious.

Quantum stat. Mech. can be done using the 1st quantized version of N-particle system on which holes are attached to the particles.

Consider the 4 possible product wave functions

$$\begin{array}{ll} \psi_a(r_1) \cdot \psi_a(r_2) & \text{I} \\ \psi_u(r_1) \cdot \psi_u(r_2) & \text{II} \\ \psi_a(r_1) \cdot \psi_u(r_2) & \text{III} \\ \psi_u(r_1) \cdot \psi_a(r_2) & \text{IV} \end{array}$$

4 dimensional vector space equally well spanned by

$$\begin{array}{l} \text{Symmetric (S)} \\ \text{antisymmetric (A)} \end{array} \left\{ \begin{array}{ll} \psi_a(r_1) \cdot \psi_a(r_2) & \text{V} \\ \psi_u(r_1) \cdot \psi_u(r_2) & \text{VI} \\ \frac{1}{\sqrt{2}} (\psi_a(r_1) \cdot \psi_u(r_2) + \psi_u(r_1) \cdot \psi_a(r_2)) & \text{VII} \\ \frac{1}{\sqrt{2}} (\psi_a(r_1) \cdot \psi_u(r_2) - \psi_u(r_1) \cdot \psi_a(r_2)) & \text{VIII} \end{array} \right.$$

Now for two electrons under a symmetric Hamiltonian symmetry character of wavefunction is relevant.

So if we impose an initial condition S or A then only one of the 2 states VII, VIII is available to the system. This is why stat. weight attaching to the pair of states VII, VIII gets halved.

The statistical weight in Q. Stat. Mech. can be regarded as reflecting dynamical restrictions on the accessibility of certain states.

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N.B Indistinguishability \Rightarrow observables are symmetric functions of particle labels.

The Indistinguishability Principle (IP)

Two particles are indistinguishable if, on average
& at any label permutation P , and any state Φ
* $\langle P\Phi | Q | P\Phi \rangle = \langle \Phi | P | \Phi \rangle$
 $(|P\Phi\rangle \equiv P|\Phi\rangle$

But $\langle P\Phi | Q | P\Phi \rangle = \langle \Phi | P^{-1} Q P | \Phi \rangle$ and P is unitary.
 $\Rightarrow QP = PQ$, i.e. permutation and Q , so
 Q is symmetric operator.

So indistinguishability implies in a restriction on observables. \rightarrow Parastatistics - Messiah & Greenberg (1965)

Note that $P|\Phi\rangle = \pm |\Phi\rangle$ is a sufficient condition for * to hold, whatever the symmetry properties of Q

This is the older view on which IP was interpreted as a restriction on states led to various problems as they arose.

Connection between para particles & para fields

Stolt & Taylor (1970a) classified para particles into 3 types (1) para bosons finite order
(2) para fermions

(3) para particles infinite order
Stolt & Taylor (1970b) showed formal equivalence (1) and (2) with Green's parafields. Field theory of parafields is still conjectured to be possible.

So we (probably) have situation of underdetermination
as between particles, field approaches to
indistinguishable particles.

N.B. In classical mechanics (in field version
for example) we can also understand
particles in terms of phase-space
continuity of trajectory (of the spikes).
This approach is not available in QFT
due to overlapping wave packets of 1-particle
states. For very dilute gas this overlap can
be neglected & S.M. Med equivalent to classical
Boltzmann results emerge.

Vacuum and Virtual Particles

So far we have agreed for underdetermination
between field v. particles approaches

But what about vacuum state $|\Phi_0\rangle$
— no particles present. Is $|\Phi_0\rangle$ a
state of non-being, of complete quiescence.

But on field approach there develops
vacuum fluctuations as local disturbances
~~which are not diagonal~~ which the no-particle
state is not an eigenstate.

Of ground state of harmonic oscillator
for which $\sigma = \sqrt{\langle q^2 \rangle \langle p^2 \rangle} = \sqrt{\frac{\hbar}{2m\omega}}$
for angular frequency ω .

- 1) Vacuum fluctuations are responsible for zero-point energy.
- 2) Vac. fluctuations explain, e.g., Lamb shift & anomalous magnetic moment of the electron, e.g. (Weissenberg) Koba (1949)
- 3) Casimir effect (1948) experimentally confirmed by Sparnaay (1958)
Attraction between uncharged conducting plates - Zero-point energy effect.

But all these results can be explained on an extended particle interpretation which allows for quantization of fields not described in the particle interpretation via the Fock-space machinery.

Virtual particles. Consider vacuum $|\Phi_0\rangle$ of coupled fields - least eigenstate of $H_0 + H_{\text{int}}$ interaction Hamiltonian

$|\Phi_0\rangle$ can be expanded as superposition of $|\Phi_0\rangle$ and appropriate many-particle eigenstates of H_0 . These are called

virtual particles. $|\Phi_0\rangle$ contains no real particles, only virtual particles.

Indeed, virtual particles correspond to internal lines of Feynman diagrams
external lines correspond to real (free) particles

4- momenta conserved at each vertex
but not at virtual particles as not a
the mass-shell defined by $p_4^2 = e^2(p_1^2 + p_2^2 + p_3^2) = m^2 e^4$

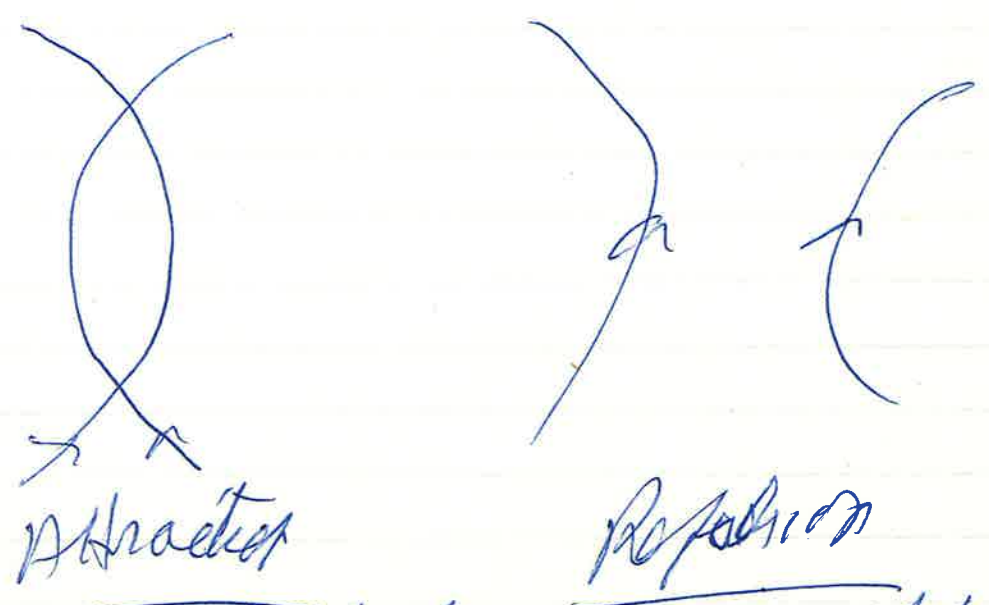
cf older non-covariant perturbation theory
in which virtual particles were on
the mass-shell but did not conserve
energy in their creation and annihilation.

iv Virtual particles arise in solving a
problem specified by $H_0 + H'$ in terms
of solutions of problem specified by H_0
alone.

N.B. No direct connection with vacuum
fluctuations which occur in the
absence of interactions.

Why does exchange of virtual particles
not always produce repulsion?

Because in momentum space we cannot
tell at which side particles pass
each other



Indeed condition for well-defined scattering is that
uncertain in transverse location \rightarrow large time of force.

Conclusion

1) Continuents reidentified in terms of TI

Spherules Distinguishable at a given instant of time but reidentifiable only if state-^{but not particle} ~~temporal~~ ^{continuity} applies - e.g. moving wave packet.

But A collection of particles is a single spherule - this is zero in which elementary particles are bereft of individuality

Spherules can be created as doctored without the awkward notion of starting and stopping a continuum.

2) Particles as labelled individuals only possible if TI assumed, provided EM state-~~temporal~~ ^{continuity} is taken as example.

But if portions for example of individual states are allowed, or hidden parameters TI might not have to be assumed.

NB. For bosons and fermions ~~at~~ 2 particles always are in same state in sense that each particle of each 1-particle state with equal probability weight. This assumes 1-particle magnitudes are ontologically available, although not as observable. But for higher-order non-particle this is not true unless we restrict {physical magnitudes} to {observables}.

So any philosophical argument against TI
(do not know what it means e.g.) will
count against particle approach to QFT.

3) Heuristic Role of Field Approach

Euphoria is a local quantities - both
very artificial from particle point of
view not being designed in the particle
representation.

Developers of QFT have counted in
taking the field properties seriously
and letting it lead us in directions
which are natural within the framework
(e.g. soft-energy effects, vacuum polarization
etc.).

4) Amplified attitude to QFT in 1930's due
to impetus

→ patched up or renormalization programs
in late 1940's.

But in strong interactions nothing could be
calculated, once perturbation theory did not work

as used introduces terms they not
renormalizable.

As major success of EI)

Development of gauge theories has led
to renormalizable versions of strong
weak interactions, which can be calculated
well (due to asymptotic freedom of QCD)
- at my note at short distances.

- 5.) Moral in HSRP is never to abandon a programme too hastily in the light of
- inconsistency (as in finiteness)
 - lack of good prediction due to the Computation gap.

Concluding remarks

In a sense nothing has happened in QFT since around 1930. In Kuhnian terms there has been no revolution, no paradigm switch (But cf the rival S-Matrix programme in the 1960s) — just a gradual working out of the immense and really unsuspected technical resources of the theory. But in respect of the interpretation of QFT, what the formalism really commits us to, ontologically speaking, there has been too much rhetoric and too little informed and critical discussion. The object of this paper has been to entice (and assist) philosophers who would like to join in the arguments.